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# Energy Storage and Smart Energy Systems

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**ABSTRACT**

It is often highlighted how the transition to renewable energy supply calls for significant electricity storage. However, one has to move beyond the electricity-only focus and take a holistic energy system view to identify optimal solutions for integrating renewable energy. In this paper, an integrated cross-sector approach is used to argue the most efficient and least-cost storage options for the entire renewable energy system concluding that the best storage solutions cannot be found through analyses focusing on the individual sub-sectors. Electricity storage is not the optimum solution to integrate large inflows of fluctuating renewable energy, since more efficient and cheaper options can be found by integrating the electricity sector with other parts of the energy system and by this creating a Smart Energy System. Nevertheless, this does not imply that electricity storage should be disregarded but that it will be needed for other purposes in the future.

***Key words:***

Smart energy systems
Energy Storage
Renewable energy
Heating
Transportation
URL:
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***Abbreviations***

| | |
|---|---|
| CAES | Compressed air energy storage |
| CHP | Cogeneration of heat and power |
| NaS | Natrium Sulphur (Sodium Sulphur) electricity storage |
| PHS | Pumped hydro storage |

## 1. Introduction

The transition from a fossil fuel- to a renewable energy-based energy system is a change from utilising stored energy to tapping fluctuating energy sources that must be harvested when available, and either used instantaneously, or stored until the moment of use. Dealing with this basic condition of the ongoing system change, it is often highlighted how a transition into a 100% renewable energy supply or even less ambitious large-scale integration of renewable energy into the energy system calls for a new magnitude of energy storage. Especially within the electricity supply, a smart grid approach has focused on the need for electricity storage [1–3] in combination with flexible electricity demand and the expansion of transmission lines to neighbouring areas [4]. Sometimes it is even stated that renewable energy is not a viable option unless electricity can be stored [5]. Similarly, Locatelli et al. state *“Electrical Energy Storage Systems (ESS) are one of the*

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*most suitable solutions to increase the flexibility and resilience of the electrical system"[6] and Tan et al. "point out smart [..energy storage systems] is a promising technology for [..micro grid] and smart grid applications"* [7].

A key problem with much of the literature in relation to storage and renewable energy systems is their tendency to focus only on the generated fluctuating electricity and its direct storage from a smart grid approach. Even though the term smart grid can refer to different types of grids, it has for many years been associated exclusively with smart electricity grids, while other potential smart grid types, gas and thermal have been neglected. Electricity storage is and will be an important part of the renewable energy system puzzle but electricity's conversion to different storable and transportable energy carriers is crucial in order to transit to 100% renewable energy supply. The overall design of the energy system needs to be rethought as for the integration of flexible generation, different conversion technologies and grid solutions.

Therefore, in order to identify the best solutions one has to move beyond the simple smart grid approach and take a more holistic view as suggested by some authors [8–12]. Electricity storage [13], flexible electricity demand [14] and transmission capacity [15] have either limited integration capacity or are associated with higher costs or actual opposition as in the case with transmission grid expansion [16].

## 2. Scope, methodology and structure

This paper investigates the most efficient and least cost storage options as a part of a Smart Energy Systems Approach, as defined in [17]. By using this approach it is explained why the best storage solutions can be found by integrating the individual sub-sectors of the energy system. One of the main reasons why a cross-sector approach can identify more economically viable solutions is the cheaper and more efficient storage technologies that exist in the thermal and transport sectors, compared to the electricity sector.

The paper is written as a synthesis of the authors' previous research within the field, thus putting forward and integrating analyses and results into a comprehensive line of argument investigating first storage in different parts of the energy system, then size and cost of storage in the energy system followed by the role of thermal storage in smart energy systems. The discussion is broadened to the integration of cooling, transportation and biomass into the energy system, ending with findings on what can be accomplished at an energy systems level by utilising a smart energy systems approach with proper use of storage.

For optimal system configurations, all potential decision variables should be considered using some sort of heuristics [18], however this article focuses on the potential role of storage across the energy system as well as the benefits from integrating traditionally separate parts of the energy system – without locating specific optimal system configuration.

## 3. Electric, thermal, gas and liquid energy storage

This section looks in to electric, thermal, gas and liquid storage from an investment, efficiency and sizing perspective.

### 3.1 Cost and efficiency of energy storage options

There is a fundamental cost difference between storing electricity and storing other forms of energy. Here electricity storage is defined as a storage in which inputs and outputs are electricity even though typically electricity is converted to other forms of energy in the process.

Figure 1 shows the typical cost of electricity storage compared to thermal, gas and liquid fuel storage technologies. There is a variety of different technologies and sizes within each type of energy storage, which influences the investments and operation and maintenance costs. Even though the exact costs vary, the magnitude of these differences does not change significantly, with the costs indicating that thermal storage is 100 times cheaper in terms of investments per unit of storage capacity, compared to electricity storage. Moreover, gas and liquid fuel storage technologies are again substantially lower in investments than a thermal storage per unit of storage capacity. Note that the costs for these latter are based on underground natural gas caverns and oil tanks, however in a future renewable energy system this can also be methane or methanol produced from biomass and hydrogen from electrolysis or similar sorts of renewable energy-based fuels [19].

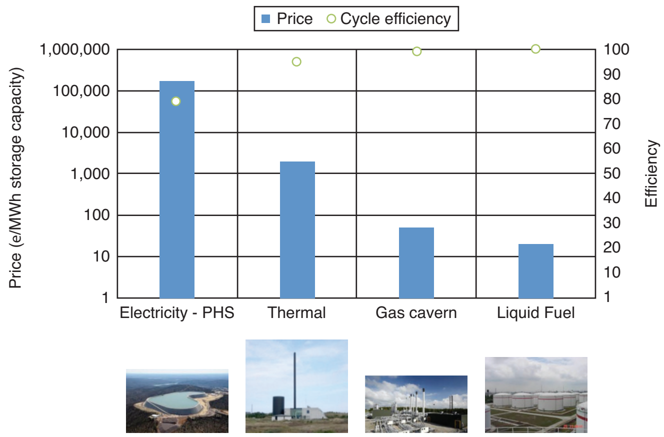


Figure 1: Investment cost and cycle efficiency comparison of electricity, thermal, gas and liquid fuel storage technologies. See assumptions, details and references in Appendix 1.

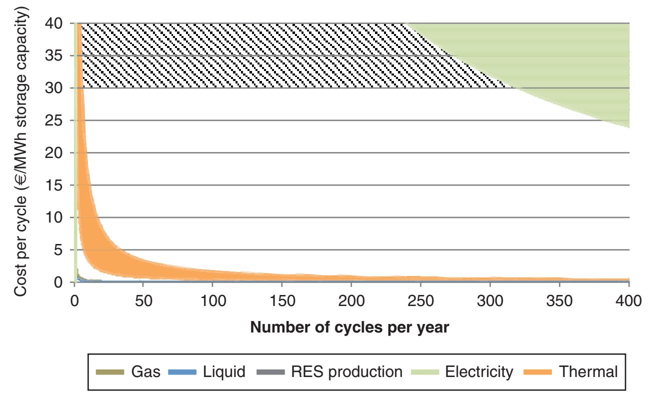


Figure 2: Annualized investment cost per use-cycle vs annual numbers of use-cycles. In the diagram the cost is also benchmarked against the cost of producing renewable energy, here shown for a wide cost span by grey (extension along horizontal axis is for presentation only; there is no cyclic dependence for renewable energy production). See assumptions, details and references in Appendix 1.

In addition to the investment issue, electricity storage is prone to significantly higher losses than any of the other types of energy storage, particularly in conversion losses. Gas caverns and oil tanks have practically nil loses; thermal storage has losses of maybe 5 percent depending heavily on size and retention time – however as electricity in almost all instances include conversion to and from the storage, losses are much more significant here.

As a consequence of investment costs and losses, the economic feasibility of electricity storage technologies depends highly on the variation in electricity prices, typically on a daily basis. However, the nature of fluctuating renewable electricity sources, such as wind power, does not typically generate such price variations. Therefore even in a system with a high share of wind power, such as the Danish case, studies show that investments in electricity storage are not feasible for the simple reason that the storage will not be used often enough to justify the relatively high initial investments [20].

Figure 2 shows how the per-use-cycle annualized investment costs of storing different forms of energy vary with the number of use cycles per year. The diagram is based on large storage technologies and shows how investment in electricity storage capacity in general requires annual cycles of at least 300-350 (equal to nearly once a day) to be able to match the cost of producing renewable energy as indicated by the hatched area. When comparing the cost of storing to the cost of producing renewable energy it should be noted that even though the electricity storage investment costs at e.g. 400 cycles per year are below the upper cost range of producing renewable energy, these storage costs include the purchasing of power to fill the storage and the operation and maintenance of the storage – nor the storage or conversion losses involved. Thus even without losses and if there is a freely available electricity source, initial investment costs in electricity storage are so high that power from the storage will only be on par with renewable electricity production if used nearly daily.

On the other hand, thermal storage investments and especially gas and liquid fuel storage are also feasible when storing energy with significantly fewer annual cycles. Here energy can be stored for weeks, months and even years due to investment costs which are even smaller. Thus, the feasibility of these other energy storage technologies is much better, especially when the energy system is rearranged to connect renewable energy to thermal, gas and/or liquid storage technologies.

Clearly, electricity storage has a more direct effect on the ability of the energy system to integrate fluctuating renewable electricity sources such as wind power [21], so a comparison cannot be made simply based on investment costs, cycle efficiencies and investment costs per cycle as shown in Figures 1 and 2. The electricity system needs to be balanced at all times but to the extent possible other storage types are more favourable as discussed as discussed later in this paper later in this paper.

## 3.2. Community vs individual domestic storage

Figures 3 and 4 illustrate another important factor, namely that there is a large element of economy of scale in energy storage. Figure 3 shows this point for thermal storage technologies by comparing a domestic 160 litre hot water tank with a 6000 $m^3$ thermal storage used by a local cogeneration of heat and power (CHP)-based district heating company [22]. Again there is a factor of 100 difference between the investments, but this time due to scale rather than type. Moreover one should note that the local CHP plant in this case has a storage capacity equal to 4 $m^3$ for each dwelling, whereas the maximum thermal storage installed with individual heating solutions is usually less than 1 $m^3$. These individual solutions are typically restricted to 1 $m^3$ due to the space required for the tanks. If even larger thermal storage capacity is considered, such as the seasonal thermal storage installed in recent district heating-connected solar thermal plants in Denmark[2], then the unit cost of thermal storage is reduced by an additional factor of approximately five compared to the unit cost of storage for a local CHP plant.

For the communal heat storages, this of course requires the presence of district heating systems which introduces additional heat losses in the system. In Denmark, heat losses in district heating networks vary considerably from system to system depending mainly on geographic heat demand intensity, but losses are on average approximately 20%. Efficiency improvements in the system outweigh these losses [23,24] and in the future, losses may be decreased by lowering the forward temperature of district heating grids [25].

Figure 4 illustrates how this in principle is the same for electricity storage technologies, even though the economy-of-scale influence is not as substantial as for thermal storage. In addition, for gas and liquid fuel storage technologies, there is an element of economy of scale but it is not as important since the costs of these types of energy storage are already low compared to the other costs in the energy supply. Furthermore, where charging and discharging facility costs for other types of energy storage are insignificant, these are costly for electricity storage.

The important point is that, if the renewable energy system can be designed so that it avoids electricity storage altogether and instead utilizes energy that can be stored in the form of thermal, gaseous or liquid fuels, and if this can be implemented at community level rather than in individual dwellings, then it will be more feasible to develop the storage capacity needed to integrate a high share of fluctuating electricity production such as wind, wave, and solar power.

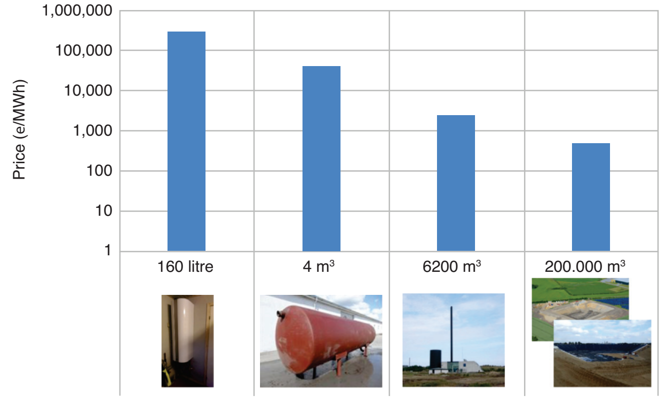


Figure 3: Investment cost comparison of different sizes of thermal energy storage technologies. The sizes correspond to storages for a dwelling, a larger building, a CHP plant and a solar DH system (see Footnote 2). See assumptions, details and references in Appendix 1.

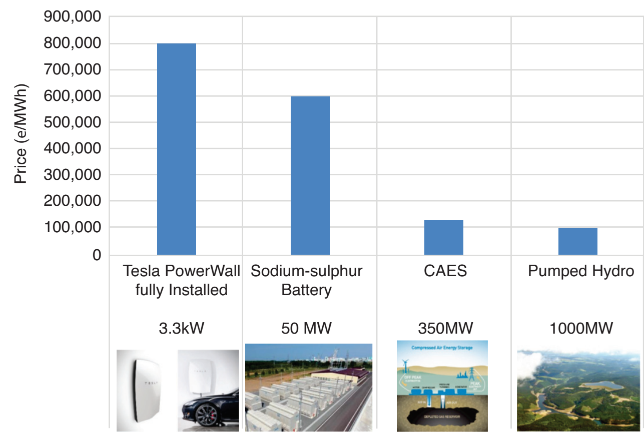


Figure 4: Investment cost comparison of different sizes of electricity energy storage technologies. See assumptions, details and references in Appendix 1.

Of course, this may come with a cost in terms of losses in energy conversion, however, these are inevitable, not only in wind or solar power integration, but in general to meet heating, cooling and transport needs in a 100% renewable energy supply [26–32]. If it is accepted that these losses are inevitable when covering heating, cooling

[2] Marstal with 2306 inhabitants on the island of Ærø has two pit stores of 10,000 $m^3$ and 75,000 $m^3$ respectively [80]. Vojens (7655 inhabitants) has recently inaugurated a 203,000 $m^3$ pit storage [81]. Dronninglund (3328 inhabitants) has a 60,000 $m^3$ pit storage[82]. All population sizes from 2014 according to [83].

and transportation demands with wind and solar power, then the losses are not occurring due to the storage of the energy, but due to the conversion of energy from electricity to heat, cooling or transportation. However, in order to identify the best and the least-cost solutions, a holistic smart energy systems approach has to be adopted.

## 4. Smart energy systems

Smart Energy Systems may be defined as *"an approach in which smart electricity, thermal and gas grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system"* [17]. Such systems encompass new technologies and infrastructures, which create new forms of flexibility, primarily in the conversion stage of the energy system. The flexibility is achieved by transforming from a simple linear approach in today's energy systems (i.e. fuel to conversion to end-use), to a more interconnected approach as shown in Figures 5 and 6. In simple terms, this means combining the electricity, thermal, and transport sectors so that the flexibility across these different areas can compensate for the lack of flexibility from renewable resources such as wind and solar.

Heat pumps in the system provides a key conversion technology between electricity and the heating sector [33–35], which combined with heat storage and the thermal mass of buildings provides flexibility for the integration of fluctuating RES-based electricity sources. Similarly, electric vehicles provides the possibility of not only a dispatchable demand but also actual electricity storage that may be fed back to the grid [36,37]. Electrofuels create a link between the electric system and transportation, so intermittent electricity production can be connected to large-scale fuel storage. Additionally, the production cycle generates heat for the heating sector thus integrating across three traditionally separate sectors.

Note that Figure 6 does not fully portray the complexity of smart energy systems to the fullest extent possible as the smart energy system is about integrating all sectors of the energy system and exploiting synergies across these.

The following sections probe further into heating, cooling and transportation, and options for adding flexibility to the smart energy system.

### 4.1. Smart heating and cooling

Although it is widely accepted that the heat demand will be reduced in the future, the steps of going all the way to eliminating the need for space heating is both technically challenging and very costly, especially as the heat demand nears zero. Therefore an essential question in the design of holistic least-cost solutions in the heating sector is to identify to which extent energy should be saved and to which extent renewable energy should be supplied as well as to which extent individual solutions should be used and to which extent communal systems like district heating should be used. In this context, not only do heat savings need to be implemented in the future, it is also important to consider how the heat supply should be provided for buildings.

Many recent research and demonstration projects have also focused on the concept of a zero energy buildings [38,39], however in order to reach these objectives one

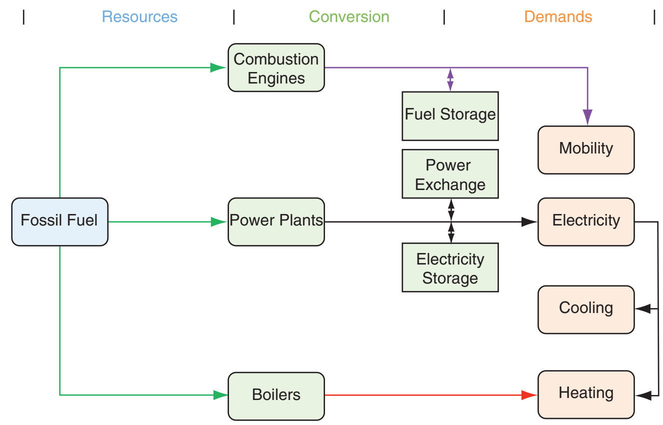


Figure 5: Today's energy systems characterised by linear paths from fuel to energy demands

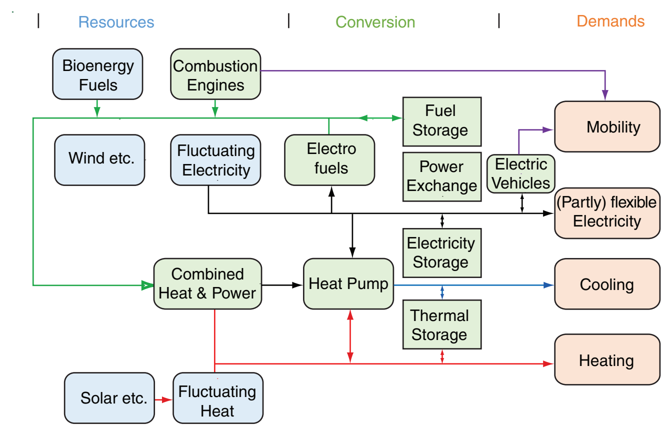


Figure 6: The integrated smart energy systems

has to include building-integrated energy supply, typically solar thermal and photo voltaic. The best solution will not be found if one considers these supplies as a part of the building; the least-cost design can only be found from a holistic smart energy approach [40].

The integration of the heating and cooling sector with electricity enables a higher fuel efficiency and increasing the share of fluctuating resources resulting in more efficient system and least-cost solutions. This becomes of even higher importance as the share of fluctuating electricity is increased towards 100% renewable energy systems.

Studies for several individual countries in Europe [41] as well as the study Heat Roadmap Europe [23,42] at the European Union level, have reached the conclusion that the least-cost way to supply heating is to combine heat savings with district heating in urban areas and individual heat pumps in rural areas. These studies also indicate that an optimal solution is to be found if savings are implemented to the level of decreasing current average heating demands by approximately 50%, although the exact number differs a bit from country to country.

The reason for applying district heating in the urban areas is that it enables obtaining the benefits of using waste heat from electricity production (CHP) and industrial waste heat [43]. Studies show that in the current system in Europe, the waste heat from electricity generation and industry is almost the same as the total heat demand of Europe [23]. As a result, by using district heating, Europe could replace half of its heating demand with waste heat and thereby save a similar share of the natural gas and oil which is currently consumed in domestic boilers.

In the future as more and more wind and similar sources replace fossil-fuel based electricity production, parts of the waste heat will come from other sources such as industry, biomass conversion and electrolysis. Moreover some heat will come from waste incineration, geothermal and large-scale solar thermal plants. However studies illustrate how the integration of wind and other fluctuating renewable electricity sources using large-scale heat pumps and thermal storage will play an important role [35,44].

The important conclusion is that power-to-heat will form an important part of the heating sector in a future renewable energy system. This applies to individual heat pumps in houses outside urban areas as well as heat pumps in district heating networks in urban areas. Similar conclusions have been made with regard to cooling [45].

One might say, that power-to-heat technology combined with dedicated heat storage or the thermal mass of buildings provide a virtual electricity storage; it can be charged when there is a high availability of renewable electricity and while it cannot be discharged back onto the grid, loads can be deferred when there is a low availability of renewable electricity.

This means that to a large extent there is the option to store renewable electricity as thermal energy at a low cost rather than at a relatively high cost in dedicated electricity storage. It will not involve any further conversion losses other than the inevitable ones that have to be accepted in any case to provide for our heating and cooling needs in the least-cost way. Furthermore, this also provides the option of increasing the integration of renewable electricity such as wind by investing in additional heat pump capacity - or to some extent also in less efficient but cheaper electric boiler capacity.

### 4.2. Smart biomass and transportation

In order to satisfy our transport needs in a future 100% renewable energy system with restricted biomass resources due to their high demand for various purposes [46–48], different power-to- transport options will play an important role [49,50]. In fact, electrification of the transport sector will form one of the most viable ways of ensuring balance between production and demand in the electricity system [51]. However not all transport demands can be satisfied by direct use of electricity and parts of the sector such as long-distance transportation, marine and aviation will continue to rely on gaseous and/or liquid fuel that will have be produced from available renewable energy resources. In order to solve this challenge creating an additional link between the electricity sector and transport is needed. Electrofuels [52] can store electricity in the form of liquid or gaseous fuels and hereby create flexibility in the system while meeting the demands of heavy-duty transport. In the process, fluctuating electricity is converted into hydrogen by the use of electrolysis and subsequently the hydrogen reacts with a carbon source from biomass (biogas or synthetic gas) or even from $CO_2$ emissions [53] to produce methane, methanol or other preferable fuels.

This enables renewable electricity storage as a gas or liquid fuel, which represents a relatively low-cost option in comparison to complex electricity storage and at the same time it provides the option of increasing the integration of wind or other fluctuating resources by investing in additional electrolysis capacity [19]. As with heating, the intention is not to supply back to the grid, but to create a deferrable load, and the conversion losses are inevitable as the energy demands for transportation needs to be meet using renewable energy sources either way.

Nastasi and Basso go as far as stating *"The Power-To-Gas option by Renewable Hydrogen production could solve the dispatch issues related to a wide deployment of RES storage devices and their priority on the energy market"* [54]

### 4.3. The overall system

Studies of complete regional, national or European energy transitions following the principles of a smart energy systems approach have demonstrated that it is possible to design 100% renewable energy systems where production and demand of renewable energy is balanced not only on a yearly basis but also on an hourly basis [28,30,55]. Such high-temporal resolution energy systems analyses have been conducted using the EnergyPLAN model [56,57] taking into account all types of energy (electricity, heating, cooling, electrofuels and other renewable energy fuels), conversion technologies between the sectors and hourly balance has been established using thermal, gaseous and liquid fuel storage.

A smart energy systems approach is also required to ensure the economic viability of future renewable energy-based energy systems. As noted in [58], wind power has the tendency to drive down spot market prices of electricity, thus undermining the very feasibility of wind power. Photo voltaics have the same effect, though the current implementation is not comparable to that of wind power in Denmark yet. A smart energy system with many deferrable loads across heating, cooling and transportation will thus increase the value of fluctuating renewable power generation.

## 5. Conclusion

The issue of energy storage is essential when discussing how to implement the large-scale integration of renewable energy both into the current system and in a future transition to a 100% renewable energy supply. A sub-sector electricity-only focus - as has been seen from a smart grid approach - typically leads to proposals primarily focused on electricity storage technologies in combination with flexible electricity demands and transmission lines to neighbouring countries. However, this paper argues that this will lead to the most expensive form of energy storage, electricity storage, which is approximately 100 times more expensive than thermal storage and even more expensive than storage for gases and liquids. It is therefore a cheaper and also a more efficient solution to utilise thermal and fuel storage technologies to integrate more fluctuating renewable energy, such as wind and solar power, than to rely on electricity storage. This however, requires a strong integration across traditionally separate energy sectors.

Thus, this paper has indicated how this cross-sector smart energy systems approach can lead to the identification of better and much cheaper options in terms of thermal, gas and liquid fuel storage in combination with cross-sector energy conversion technologies. Heat pumps, which can be in each building in the rural areas or in district heating system in the urban areas, can connect the electricity sector to thermal storage, while electric vehicles and electrofuels can connect the electricity sector to storage in the transport sector. Using these more efficient and cheaper options, it is unlikely that the other options in the electricity sector will be required solely for the integration of renewable energy. In fact, studies show that large electricity storage capacity is not economically viable for this sole purpose within any of the steps between now and a future 100% renewable energy supply.

In conclusion, for the large-scale integration of fluctuating renewable electricity sources, electricity storage should be avoided to the extent possibleis and other storage types provide an option for system balancing and flexibility while having lower costs. Direct electricity storage may be needed for other reasons but should not be prioritized if the aim is to put the electricity back to the grid.

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## *Appendix 1: Assumptions for Figures*

All data shown in Figures 1-4 are shown in Tables 1 and 2 below along with references for the data. Columns 3-6 in Table 1 are only relevant for Figure 2 and the technologies included there.

**Comment on annual costs**

All annual costs are calculated as an annuity of the investment based on a discount rate of 3 percent per year and the given lifetime plus fixed annual operation and maintenance (O&M) costs.

**Comments on electrical storage**

NaS storage is based on a ratio between installed discharge capacity and storage capacity of 6h in line with [60, 67].

Compressed Air Energy Storage (CAES) is based on a 360 MW / 1478 MWh plant.

PHS costs vary considerably from site to site. A German plant is priced at about 100,000 €/MWh [68], Electric Power research Institute lists a range from 4,40,000 to 6,00,000 US$/MWh or 3,30,000-4,60,000 €/MWh [60] at the average exchange rate of 0.755 US$/€ in 2010 [69]. As with NaS, this is based on a ratio between installed discharge capacity and storage capacity of 6h. It should be noted that PHS is by far the most used grid-connected electricity storage technology with 153 GW out of 154 GW globally [70]. Only two CAES plants are in operation – albeit both in the >100MW size range [70]. NaS experienced a ten-fold increased from on 2,000 to 2,006 thus a technology with significant development [70].

Efficiencies given in [71] for PHS are 70-80%, [60] list cycle efficiencies as 80-82% and [72] list efficiencies from 76 to 85% depending on design.

**Comments on thermal storage**

All thermal storages are calculated based on a $\Delta T=60K$ corresponding to a specific contents of 70 kWh/m$^3$. The Danish Energy Agency[71] list specific contents for large steel storage tanks and seasonal pit storages as 60-80 kWh/m$^3$.

The 6200 m$^3$ tank is an actual storage of Skagen district heating company in Denmark. The Danish Energy Agency lists costs for large steel tanks for district heating at 160-260€/m$^3$ [71] corresponding to 2,300-3,700 €/ MWh.

Costs of the 160 litre and the 4 m$^3$ tanks are based on actual bids from a supplier including installation costs. The Danish Energy Agency lists small tanks (150-500 l) at around 4€/ l - though this cost does not include installation costs [71]. This corresponds to 57,000€/MWh

**Comment on gas storage**

The costs are based on a gas cavern. For comparison, a five-cavern plant in Denmark with 5*100 million Nm$^3$ - equivalent to a total of 5.5 TWh - costs 254 M€ or 46€/MWh [71]

**Comment on fuel storage**

Storage costs vary according to local conditions including e.g. size and number of tanks, potential jetty construction, tank foundation details based on soil conditions. Based on actual tanks of Oiltanking Copenhagen, prices are in the 200-250 €/m$^3$ range.

## *Comment on production costs for renewable energy*

*As noted by [73], "cost projections [of wind, solar] are abundant [..] although with high uncertainties attached"*. Investigating data from the Danish Energy Authority and the Danish transmission system operator Energinet.dk on renewable energy technologies reveals a wide span of technology costs and thus production costs. The same technology costs are included from a 2012 assessment and a 2016 assessment to show how price expectations have changed with decreasing costs from on-shore wind - but increasing costs off-shore. Photo voltaics on the other hand have experienced a significant decrease over the same period of time.

For comparison, median scenarios for biomass prices in Denmark show costs of 6.2 €/GJ in 2015 and 7.1 €/GJ in 2030 [74] CIF[3] Danish harbour - giving a marginal fuel cost of 50-57€/MWh for a biomass condensing power plant with an efficiency of 45%. Coal - with a September 2016 price of approximately 72 US$/t [75] (64€/t) - has a fuel cost of approximately 18€/MWh based on a condensing mode power plant with an efficiency of 45%. Average CIF prices for industry in Denmark in 2015 were 382 DKK/t [76] or 50€/t - thus a fuel cost of electricity of 14€/MWh if coal prices for power plant are equal to coal prices for industrial coal users.

In Figure 6, renewable electricity production is shown as a band from 30 to 50 €/MWh.

[3] Cost, insurance and freight.

**Table 1: Characteristics for storage technologies.**

| Storage type | Investment cost [€/MWh storage capapcity] | Fixed O&M [% of investment] | Lifetime [Years] | Annual costs [€/MWh storage capacity] | Cycle efficiency |
|---|---|---|---|---|---|
| Electricity – PHS [59] | 175000 | 0.5 | 50 | 4387 | 0.80 |
| Electricity – NaS [60] | 600000 | 0.5 | 30 | 33612 | 0.85 |
| Electricity – CAES [20] | 125000 | – | – | – | – |
| Electricity – Tesla [61] | 660000 | – | – | – | – |
| Thermal – pit [62] | 500 | 0.5 | 30 | 28.0 | 0.85 |
| Thermal – large tank [63] | 2500 | 0.5 | 25 | 156 | 0.95 |
| Thermal – 4000 l [64] | 24000 | – | – | – | – |
| Thermal – 160 l [64] | 180000 | – | – | – | – |
| Gas [65] | 60 | 0.5 | 50 | 2.6 | 0.98 |
| Liquid [66] | 20 | 0.5 | 30 | 1.1 | 1.00 |

**Table 2: Wind and photo voltaic technology costs and production assumptions. Total production costs are calculated based on the other columns (and are thus not calculated by the stated references). Investment costs are calculated as an annuity using a discount rate of 3 percent. Years (2015 and 2030) refer to prognoses for the two years.**

| | Investment cost [€/MW] | Technical lifetime [Years] | Capacity factor | Fixed O&M [€/MW] | Variable O&M [€/MWh] | Total production cost | | Source |
|---|---|---|---|---|---|---|---|---|
| | | | | | | [€/MWh] | [DKK/MWh] | |
| Wind – Large on-shore 2015 | 1400000 | 20 | 0.337 | n.a. | 14 | 40 | 298 | [77] |
| Wind – Large on-shore 2030 | 1290000 | 20 | 0.365 | n.a. | 12 | 34 | 254 | [77] |
| Wind – Large off-shore 2015 | 3100000 | 20 | 0.457 | n.a. | 19 | 61 | 457 | [77] |
| Wind – Large off-shore 2030 | 2300000 | 25 | 0.502 | n.a. | 16 | 49 | 366 | [77] |
| Grid-connected PV 2015 | 2000000 | 30 | 0.091 | n.a. | 34 | 216 | 1620 | [77] |
| Wind – Large on-shore 2015 | 1070000 | 25 | 0.37 | 25600 | 2.8 | 31 | 236 | [78] |
| Wind – Large on-shore 2030 | 910000 | 30 | 0.38 | 22300 | 2.3 | 29 | 217 | [78] |
| Wind – Large off-shore 2015 | 3500000 | 25 | 0.5 | 72600 | 5.5 | 72 | 542 | [78] |
| Wind – Large off-shore 2030 | 2700000 | 30 | 0.53 | 55000 | 3.9 | 58 | 436 | [78] |
| Large grid-connected PV 2015 | 1200000 | 30 | 0.122 | 12000 | 0 | 93 | 697 | [79] |
| Large grid-connected PV 2030 | 820000 | 40 | 0.140 | 8160 | 0 | 72 | 539 | [79] |